PROBING THE SOLAR CORONA WITH RADIO RANGING MEASUREMENTS

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ABSTRACT

An asymmetry in the radial variation of electron density above the east and west limbs of the Sun was inferred from centimeter wavelength ranging measurements conducted by Voyager 2 during its 1985 solar conjunction (Anderson et al. 1987). The Voyager 2 ranging measurements, that took place in the heliocentric distance range of 7-40 R_o, have been compared with the white-light coronagraph measurements of the underlying corona collected by the Mark III K-coronameter located at the Mauna Loa Solar Observatory. It is shown that the disparity in radial profiles off the east and west limbs is not real, but instead an artifact caused by the longitudinal variations revealed in the white-light measurements. An improved understanding in the probing abilities of ranging measurements and their relationship to white-light measurements is obtained. The results reinforce the notion that, the high precision and high sensitivity features of ranging measurements are more fully exploited in the investigation of density variations across low-contrast ray-like structures in the corona rather than in determining radial density profiles.

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1. INTROIIUCTION

Conducted with both natural radio sources and spacecraft radio signals, centimeter wavelengt h ranging or time delay measurements have successful 1 y probed the solar corona for over twenty years. These measurements are similar to white-light coronagraph measurements in that both observe path-integrated electron densit y. While white-light measurements provide an image of the corona in the plane of the sky, ranging probes only a point of this image. However, by virtue of its superior precision and sensitivity, especially when conducted with spacecraft radio signals, ranging is able to reliably observe slight changes in the corona well beyond the field of view of coronagraphs. These features have been exploited in investigating the radial dependence of electron density over a wide range of heliocentric distances (Counsehnan and Rankin 1972, Muhleman et al. 1977, Edenhofer et al. 1977, Tyler et al. 1977, Esposito et al. 1980, Muhleman and Anderson 1981, Anderson et al. 1987, Krisher et al. 1991, Bird et al. 1994). Precisely determined density profiles from such measurements could play a role in understanding the flow properties of the solar wind by constraining, solar wind models in the upper corona, as has been demonstrated with white-light measurements in the lower corona (Habbal et al. 1995).

The purpose of this Letter is to examine more closely the density profiles derived from ranging measurements. Of particular interest are those inferred from the 1985 Voyager 2 solar conjunction measurements, which took place near the solar equator, and were consequently free of latitudinal variation. When the ranging measurements from the ingress and egress (corresponding to probing the corona above the east and west limbs of the Sun, respectively) portions of the conjunction were compared, a significant asymmetry in the deduced radial dependence of electron density was found (Anderson et al. 1987).

The disparity in the Voyager 2 density profiles is investigated in Section 2, and shown to be the consequence of longitudinal variation. These results are placed in the context of recent gains in the global picture of coronal structure in Section 3. A more complete understanding of the probing abilities of ranging measurements and their relationship to white-light measurements has emerged, and this is summarized in Section 4.

2. 1985 VOYAGER 2 OBSERVATIONS

Reproduced in Fig. 1 are the 1985 Voyager 2 solar conjunction ranging measurements that took place in the heliocentric distance range of '/-40 $R_{\odot}$. The ingress (cast limb) and egress (west limb) portions are shown in Figs. 1 a and 1 b, respectively. For the sake of more direct comparison, the two sets are also displayed together in Fig. 1 c. The corresponding day of year (DOY) on which the measurement was made is indicated alongside each data point. The asymmetry in the radial dependences of these two sets of data is evident from the power-law fits, showing a radial variation of $R^{-2.6}$ for the ingress measurements and a radial variation of $R^{-2.0}$ for the egress measurements.

To interpret the Voyager results in Fig. 2, a comparison with simultaneous white-light measurements would be useful. Fortunate y, measurements of the under] ying corona during Barrington Rotation 1769 were collected by the Mark III K-coronameter located at the Mauna Loa Solar Observatory in Hawaii. The corresponding synoptic maps of the polarized brightness pB observed on the east and west limbs at a height of 1.3 R. arc reproduced in Figs. 2a and 2b, respectively (Sime et al. 1986). Individual daily images of the white-light corona during this period were also kindly provided by J. Burkepile of HAO. The main contribution to the path-integrated density measurements for an approximately spherically symmetric corona comes from the corona near the closest approach point. Corresponding closest approach points for the Voyager 2 measurements have been mapped back to the Sun assuming a constant solar wind speed of 450 km/s. These points are marked by their respective DOY. The 1985 Voyager 2 measurements took place during the low activity portion of the solar cycle when Doppler scintillation measurements indicated a general low occurrence ı ate of transients (Woo 1993).

Specifically, SMM white-light coronagraph observations (Burkepile and St. Cyr 1993) showed no coronal mass ejections in the vicinity of the regions probed by the Voyager measurements. The variations in the Voyager 2 ranging measurements are, therefore, caused mainly by spatial rather than temporal changes. It should be stressed that although the Mauna Loa and Voyager 2 measurements of the corona took place at the same solar coordinates and at the same time, the white-light measurements observed the lower corona, while the Voyager 2 measurements observed the outer corona. Still, since the ranging measurements probed the extensions and consequences of the large scale structures (streamers and coronal holes) seen in the lower corona, a reasonably high correlation would be expected.

Examination of the source regions of the corona observed by Voyager 2 as depicted in the white-light maps of Fig. 2 makes it clear that they have influenced the radial profiles of the density. For instance, the radial dependence estimated from the ingress measurements is exaggerated and steeper because the measurements nearest the Sun (DOY 342) probed a streamer where the density is high, while the measurements farthest from the Sun (DOY 333 and 334) probed a low latitude coronal hole region where the density is low. Although the egress measurements observed the same source region after it had rotated to the west limb, the geometry was such that the measurements closest and farthest to the Sun were both in high density streamer regions, thus resulting in a less steep radial dependence. Consistency is also found when the relative differences between the ingress and egress measurements at the same heliocentric distance are compared with those between the east and west 1 imb white-light measurements. For example, the white-]ight maps indicate that the density in the lower corona on DOY 342 is higher than that of DOY 346, as is the case in the higher corona depicted in Fig. 1 c. The white- light maps also show that, in the lower corona, the density on DOY 352 is higher than that on DOY 334, and again this is borne out in the ranging measurements of the higher corona in Fig. 1 c.

Although free of temporal and latitudinal variations, the radial dependence of the ranging measurements displayed in Fig. 1 obviously includes the longitudinal variation of path-integrated density as well. Furthermore, the asymmetry in the apparent ingress and egress radial profiles is a direct consequence of this longitudinal variation.

3. SOLAR CORONA AND RANGING MEASUREMENTS

Let us discuss the Voyager 2 results in light of recent advances in our knowledge of the the corona, The corona is permeated by ray-like structures, starting with the large-scale structures such as coronal streamers and plumes observed in white-light coronagraph pictures and extending down to sizes as small as 1 km (1 milliarcsec) at the Sun (Woo 1995a). Representing only a small percentage of the mean, small-scale structures arc masked in the measurements of density. Thus, like polarized brig, htness in the case of white-light measurements, ranging effectively sees only the large-scale structures such as streamers and plumes (Woo 1995b).

In the upper corona, peaks in path-integrated density correspond to the extensions or stalks of coronal streamers, while the minima occur in the coronal hole regions (Woo et al. 1995a). Near the ecliptic plane, both ranging and white-light measurements show that path-integrated density decreases by only a factor of about two from streamer to coronal hole region (Woo et al., 1995a; Woo 1995b, Guhathakurta and Fisher 1995). This relatively weak longitudinal dependence is the reason for the genera] consistency often found between the shapes of electron density profiles inferred from ranging measurements of the low-latitude corona despite the presence of longitudinal variations (Bird et al. 1994). The 1985 Voyager 2 measurements were unusual in that the disproportionate influence exerted by the few measurements in significantly different source regions led to extremes in density profiles observed.

Coronal mass ejections, many of which include interplanetary shocks, cause temporal changes (transients) in ranging measurements. Because the enhancement in density in a coronal mass ejection is generally smaller than the enhancement in density fluctuations caused by turbulence, transients near the Sun are usually less conspicuous in ranging or phase than in scintillation measurements (Woo and Armstrong 198 1; Woo et al. 1985). This may also be the reason for evidence showing that shocks are detected in radio scattering measurements sensing density fluctuations before they are in white-light measurements sensing density (Woo et al. 1982). Although there is evolution with heliocentric distance, in situ plasma measurements have shown similar behavior at the orbit of Earth (Huddleston et al. 1995). This explains why Doppler scintillation measurements have generally been more effective in detecting and investigating transients and coronal mass ejections than ranging measurements. Since the frequency of occurrence of transients observed by Doppler scintillation is generally low (Woo 1993), limited ranging data sets, such as the one in the case of Voyager 2, are often free of transients.

4. CONCLLJS1ONS

Although ranging measurements of the solar corona have been conducted for over 20 years, a more complete understanding of their probing abilities and relationship to white-light measurements is just now emerging. Developed originally by the NASA Deep Space Network for the precise navigation of interplanetary spacecraft, ranging measurements have advantages over white-light measurements in sensitivity, precision, spatial resolution, and dynamic range.

The high sensitivity of ranging measurements makes it possible to investigate path-integrated electron density over an extensive heliocentric distance range. Unfortunately, although the dominant variation is radial, ranging measurements also include variations in solar longitude and latitude (in the case when the radio source is out of the ecliptic). It is the longitudinal variation, stemming from the probing of significantly different source regions, that gave rise to the apparent disparity in ingress and egress density profiles inferred from the Voyager 2 measurements. Thus, in spite of yielding precise measurements of path-integrated density, ranging alone cannot reliably measure separate density profiles for coronal holes and streamers, as has been done in the case of white-light coronagraph measurements of the lower corona (Guhathakurta and Fisher 1995). Such information can only be obtained by conducting ranging measurements simultaneously with multiple spacecraft at different heliocentric distances, or in conjunction with coronal imaging by white-light.

When the radial dependence is removed, the high precision feature of ranging measurements makes it possible to observe the low-contrast density variations across large-scale ray-1 ike structures in the corona. This has been demonstrated in the detection and investigation of plumes in an equatorial coronal hole region (Woo 1995b, Woo et al. 1995c). So far, measurement uncertainties have precluded the detection of plumes in the low-latitude corona by white-light measurements (Guhathakurta and Fisher 1995). The high precision and high sensitivity features of ranging measurements are, therefore, more fully exploited when investigating the large-scale density variations transverse to the ray-like structures, rather than the radial variation of density.

Although smaller-scale structures can be observed by increasing the sampling rate of the ranging measurements, they are dwarfed by the large-scale structure, and arc more readily revealed in measurements that detect density gradients (Koutchmy 1977, Guhathakurta and Fisher 1995, Woo et al. 1995b). With ranging measurements, density gradients are most easily seen via the time derivative (Woo et al. 1995a). However, since phase measurements can be sampled at higher frequencies (corresponding to higher spatial resolution), and arc even more precise than ranging measurements, phase and Doppler (time derivative of phase) measurements are the preferred radio propagation measurement for studying small-scale structure (Woo et al. 1995b). Such measurements complement the large-scale measurements of white-light, and coordinated Doppler scintillation measurements arc being planned in conjunction with the white-light measurements of the SOHO mission (Woo 1994).

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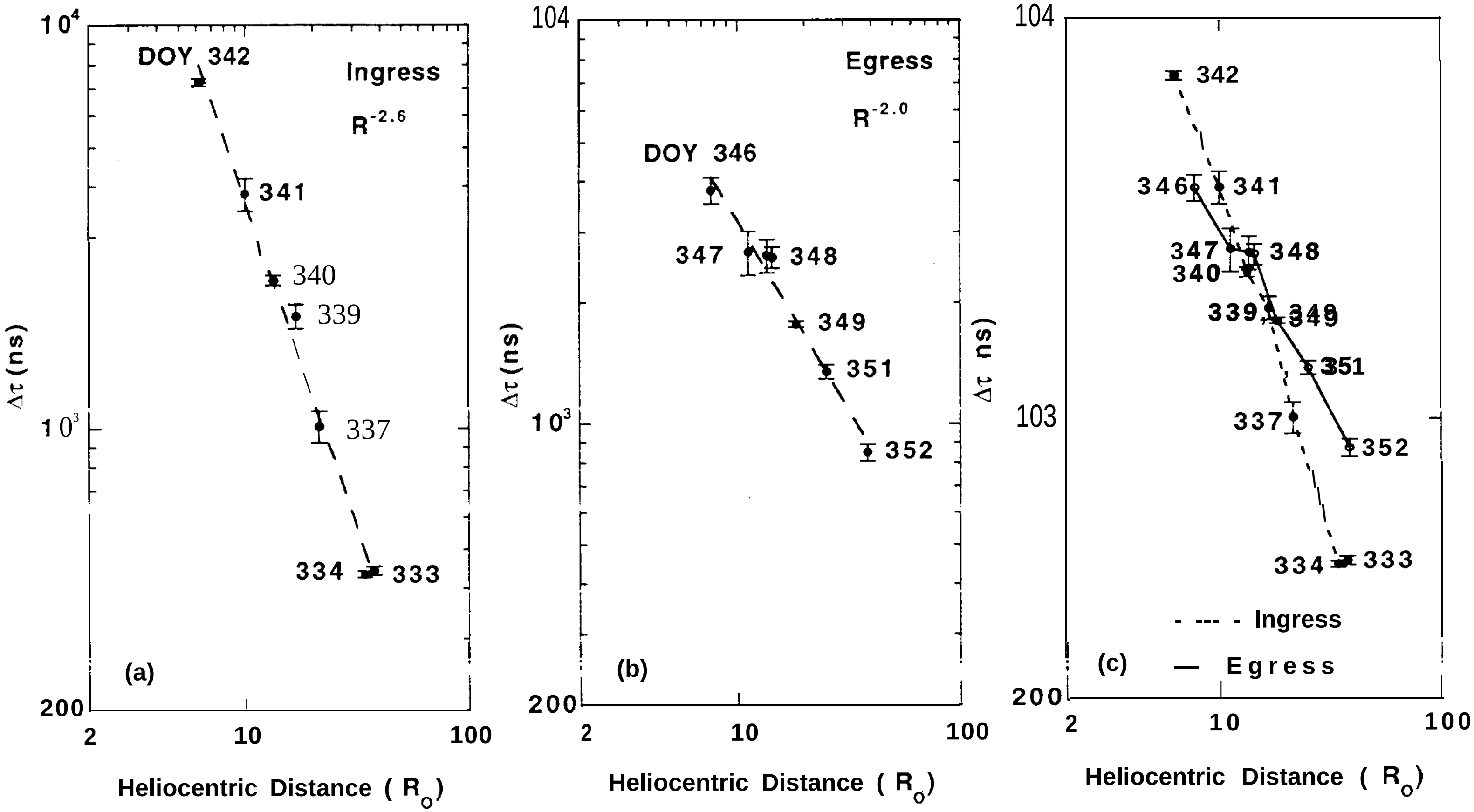
FIGURE CAPTIONS

Figure 1. Radial profiles of time delay (path-integrated electron density) during the (a) ingress (east limb), and (b) egress portions of the 1985 solar conjunction of Voyager 2, obtained by Anderson et al. (1987). The two profiles are plotted t ogether in Fig. 1c for convenience of comparison. The numbers adjacent 10 the data points indicate day "of year (DOY) on which the measurements were made. The cast limb (ingress) data show a radial variation of $R^{-2.6}$, while the west limb (egress) data show a radial variation of $R^{-2.0}$.

Figure 2. HAO Mauna Loa Solar Observatory Mk 111 K-coronameter synoptic contour maps of polarized brightness pB at a height of 1.3 R. from Sime et al. (1986) based on east (upper plot) and west (lower plot) measurements. The black dots on the K-coronameter maps indicate the closest approach points of the Voyager 2 radio paths mapped back to the Sun for the corresponding limb. The numbers adjacent to the black dots indicate corresponding DOY of measurement.



DOY 342
Ingress
$R^{-2.6}$
341
340
339
337
334
333
(a)
10^4
10^3
200
2
10
100
Δτ (ns)
Heliocentric Distance (R_o)
Egress
$R^{-2.0}$
DOY 346
347
348
349
351
352
(b)
104
10^3
200
2
10
100
Δτ (ns)
Heliocentric Distance (R_o)
342
346
341
347
348
340
339
349
349
351
351
337
352
334
333
- --- - Ingress
— Egress
(c)
104
103
200
2
10
100
Δτ (ns)
Heliocentric Distance (R_o)

HIGH ALTITUDE OBSERVATORY MAUNA LOA

MK III K-CORONAMETER

ROTATION 1769 HEIGHT 1.3 $R_{\odot}$